IMPROVED CONTROL STRATEGY OF GRID INTERACTIVE INVERTER SYSTEM WITH LCL FILTER USING ACTIVE AND PASSIVE DAMPING METHODS

A THESIS SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Electrical Engineering

By

M. LAKSHMI SOWJANYA

Department of Electrical Engineering

National Institute of Technology, Rourkela

2012-2014

IMPROVED CONTROL STRATEGY OF GRID INTERACTIVE INVERTER SYSTEM WITH LCL FILTER USING ACTIVE AND PASSIVE DAMPING METHODS

A THESIS SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Electrical Engineering

By

M. LAKSHMI SOWJANYA

Under the Guidance of

Prof. B. Chitti Babu

Prof. K. B. Mohanty

Department of Electrical Engineering

National Institute of Technology, Rourkela

2012-2014

Department of Electrical Engineering

National Institute of Technology Rourkela

CERTIFICATE

This is to certify that the thesis entitled “**IMPROVED CONTROL STRATEGY OF GRID INTERACTIVE INVERTER SYSTEM WITH LCL FILTER USING ACTIVE AND PASSIVE DAMPING METHODS**” submitted by Miss. **M. LAKSHMI SOWJANYA** bearing Roll no 212EE4393 in partial fulfillment of the requirements for the award of Master of Technology Degree in Electrical Engineering with specialization in “**Power Electronics and Drives**” during session 2012-2014 at the National Institute of Technology, Rourkela is an authentic work carried out by her under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Date: Prof. K. B. Mohanty

Place: Rourkela Supervisor

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my supervisor **Prof. B. Chitti Babu** for his guidance, encouragement, and support throughout the course of this work. It was a valuable learning experience for me to be one of his students. From him I have gained not only extensive knowledge, but also a sincere research attitude. I also like to express my sincere gratitude for my co-guide **Prof. K. B. Mohanty** for his encouragement and constant support.

I express my gratitude to **Prof. A. K. Panda,** Head of the Department, Electrical Engineering for his valuable suggestions and constant encouragement all through the research work.

My thanks are extended to my colleagues in Power Control 'N' Drives, who built an academic and friendly research environment that made my study at NIT, Rourkela most memorable and fruitful.

I would also like to acknowledge the entire teaching and non-teaching staff of Electrical Department for establishing a working environment and for constructive discussions.

Finally, I am always indebted to all my family members, especially my parents, for their endless love and blessings.

M. Lakshmi Sowjanya

Roll No: 212EE4393

Department of Electrical Engineering

National Institute of Technology

Rourkela-769008

Dedicated to My Beloved

Parents and Respected Teachers

CONTENTS

Title **Page No**

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS USED

RES	Renewable Energy Source
PI	Proportional Integral
PR	Proportional Resonant
THD	Total Harmonic Distortion
IEEE	Institute of Electrical and Electronics Engineers
AI	Artificial Intelligence
kW	Kilo Watt
Hz	Hertz
mH	Mille Henry
μF	Micro Farad

ABSTRACT

The shortage of electric power is the major problem now-a-days. As the conventional energy sources are depleting at a faster rate, there is an urgent need to investigate the alternative energy sources which help to solve the problem. The Renewable Energy Sources (RES) like wind, solar, tidal, bio mass etc., serve this purpose. But these are intermittent in nature and cannot be integrated to the present utility grid directly.

Thus, to overcome the above problem power electronic converters are used. These converters should be controlled in such way that the stability of the overall system is maintained.

In this project, the control of grid connected inverter with LCL filter is studied. The LCL filter is an effective solution for the interconnection of the RES to the grid but suffers from the problem of resonance. To overcome the above drawback active and passive damping methods are proposed. And also a control strategy to reduce the lower order harmonics is proposed. The proposed control strategy is simulated in MATLAB SIMULINK environment.

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

At present, there is an exponential rise in the power demand and to meet this demand the existing energy resources are not sufficient. And also these resources are depleting day-by-day. So there is an urgent need to develop the power generation from Renewable Energy Sources (RES) which provide a reliable alternative for the conventional energy sources.

These also have the advantage of cleaner energy production by reducing carbon emission, thereby being environmental friendly. But the main drawback of these RES is their intermittent nature, which causes difficulty in extracting power all the time in a day. As these are the only option left to meet the increasing energy demand, they (RES) should be modeled in such a way to overcome this drawback.

These RES are synchronized to the grid through a dc-link and an inverter. To ensure stable operation of the grid, the voltage and frequency of the power injected by the RES should match with that of the grid. To achieve this, perfect control of the grid-side inverter is required in spite of the intermittent nature of RES. This project presents the modeling of the grid side inverter and proposes a control strategy for better synchronization of the RES to the grid.

1.2 RESEARCH MOTIVATION

The RES are used as alternative energy sources now-a-days. Due to the intermittent nature of these sources, the characteristics of the power generated by RES are quite different from that provided by conventional power plants [1]. As a result, the stability and reliability of the whole power system is affected by the increasing penetration level of RES. In order to minimize the adverse impact of RES, the performance of RES power plants should be regulated and their control & integration to the utility grid is utmost important and is achieved through power electronic converters [2]. Consequently, the control of the inverter should be improved to meet the requirements for grid interconnection.

1.3 LITERATURE REVIEW

The use of Renewable Energy Sources for electric power generation is an age old solution from 1992-1994. But they are used for specific applications like heating water, pumping water etc. They are not so prominent at that time and the capacity of power extracted from RES is very less. But with the development of technology and modernization there is a rapid increase in demand for electric power. The traditional energy sources like- coal, fossil fuels are not sufficient to meet this increase in demand. As a result there is a mismatch between the electric power demanded and supplied thereby affecting the stability and reliability of the overall system.

Thus to overcome the above problem, alternative energy sources should be employed and the RES are the best alternative to solve this issue. With this the importance of the RES has been increased exponentially and many new RES power plants have been established. Among the RES hydropower and wind energy has largest utilization. The wind power in many countries over the world has led to the fast development of wind turbine technology. At the end of 2004, Europe has nearly about 35-GW of installed wind power.

Another RES that gains importance without harming environment is Photo-Voltaic (PV). The recent advances in power electronics and the materials used for making PV-cells increased the use of PV panels for electric power extraction. But the main drawback of the RES is their low efficiency and controllability. As a consequence, the interconnection of RES to utility grid may cause grid instability or even grid failure. Therefore, the control strategies to control RES are of utmost important. This project presents the control of grid connected inverter to maintain the stability of the overall power system.

The control of grid connected inverter is done under two loops- Voltage control loop and Current control loop [2]. The current control loop is responsible for the quality of power injected to the grid and plays a vital role in the control algorithm. There are different current control techniques in the literature. The basic classification in current control techniques is- linear and non-linear. The non-linear current control techniques have good dynamic response but introduce a time delay. Among the linear control techniques, Proportional-Integral (PI) and Proportional-Resonant (PR) are most prominently used. The control of grid connected inverter can be carried out in various reference frames like a-b-c, d-q or α-β. Each reference frame has a unique control strategy with its own merits and demerits. An overview of the various reference frames for grid connected inverter control is given in [9]. A PI current control technique in d-q reference frame is presented in [1]. But it has the problem of strong coupling between d and q-axes currents and requires additional control circuitry. To overcome this problem, PR control technique [15] can be used. The advantage of PR controller is the possibility to implement harmonic compensator without interfering with the control dynamics. An overview of different current control techniques have been given in [22]. Among them suitable one can be used based on application.

Another major issue regarding grid integration is the harmonic content present in the output current of the inverter. To reduce these harmonics filters can be used at the output of the grid connected inverter. There are different filter topologies in the literature like L, LC, LCL etc., which can be used for this purpose. The merits and demerits of different filter configurations have been explained in [5]. Among the various available topologies, LCL filter best suits the application of grid integration of RES. The modeling and control of grid connected inverter with LCL filter has been given in [7]. Here the mathematical modeling is done in α-β reference frame.

The drawback of the LCL filter is- it may cause resonance with grid. To overcome this drawback active and passive damping methods have been proposed in the literature. The active damping method is a control algorithm which acts such a way to cancel out the resonance affect. On the other hand, the passive damping method uses physical elements such as inductor, capacitor and resistor to provide damping. An overview of the active damping method for suppressing LCL filter resonance is given in [14]. [16]-[17] also explain the active damping method to damp out the LCL filter resonance. A comparative study between active and passive damping control techniques along with different existing topologies in active and passive damping have been presented in [8]. Resonance damping of LCL filter using low pass and band pass filters is given in [11]. A new active damping strategy for LCL based grid connected inverter is presented in [23]. The active damping control algorithm is difficult to implement but it has better performance characteristics and high efficiency with reduced THD. The passive damping method suffers with reduced efficiency due to increase in power loss because of the extra passive elements. It is a low cost method and is used where the efficiency can be sacrificed slightly.

With the use of LCL filter the THD of the grid current has been greatly reduced and almost sinusoidal waveforms of grid voltage and current are obtained. But there are considerable amount of low-order harmonics present in the grid current. And also the recent solutions for grid interconnection are based on transformer less architecture. This causes the presence of DC offset component in the grid current. This value should be within permissible limits for smooth operation of the grid. To overcome this problem, a shunt connected LCL filter has been proposed in [12]. In this the LCL filter has been connected in shunt at the point of coupling between the inverter and the grid. The control strategy of grid connected inverter with shunt connected LCL filter is presented in this paper.

1.4 THESIS OBJECTIVES

The main objective is to control the grid-connected converter, through which the RES is connected to the utility grid. The objectives of the control algorithm include-

1. Minimize the harmonics in grid current
2. Reduce the voltage fluctuations at the point of common coupling (PCC)
3. Control the DC-link voltage
4. Control the active power injected to the grid
5. To ensure unity power factor operation
6. To have independent control on active and reactive power injected into the grid

1.5 ORGANIZATION OF THESIS

The thesis is organized into five chapters including the introduction. Each of these is summarized below.

Chapter 2 deals with the LCL filter used for grid interconnection of RES to the utility grid and provide the mathematical model of grid connected converter.

Chapter 3 deals with the active and passive damping methods used for damping out LCL filter resonance and provide a comparative study between the two methods during steady state condition and during source dynamics condition.

Chapter 4 deals with the reduction of harmonics in the injected grid current below the fundamental frequency and provides a control circuit for this purpose.

Chapter 5 deals with the general conclusions of the work done followed by future scope and references.

CHAPTER 2

MODELING AND CONTROL OF GRID-CONNECTED INVERTER WITH LCL-FILTER

2.1 INTRODUCTION

The Renewable Energy Sources are connected to the utility grid through a power electronic converter and a filter. The block diagram of the grid-connected RES is-

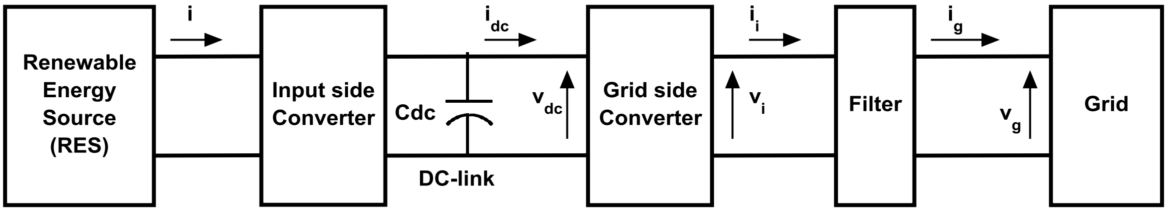


Figure2.1 Block Diagram of Grid Connected System

In Fig. 2.1 the RES may represent wind or solar panel, which generate either ac or dc. Then there is an input side converter which converts the ac power generated (in case of wind mills) to dc. Its main aim is to extract maximum power from the RES. It may contain a boost converter to boost the voltage levels to match with that of the utility grid values. The control algorithms of input side converter include MPPT techniques to extract maximum power from RES at every point of time.

The DC-link is used for providing constant dc input voltage to the grid-side converter. It contains a capacitor, C_{dc} for this purpose.

The Grid-side Converter converts the dc power to ac and feed it to the utility grid. The main aim of this converter is [1]-

- To maintain constant dc-link voltage
- To keep the frequency and phase of output current same as grid voltage

The control algorithm of this converter has the following tasks-

- To control the active power injected into the grid
- To control the reactive power transfer between the RES and the grid
- To maintain Grid Synchronization

In addition to the above main tasks, the grid-side converter also regulates local voltage and frequency, compensates the voltage harmonics and may does active filtering when required. Thus, to control the power injected into the grid, the control of grid-side converter is of utmost important. But the output current from the inverter contains harmonics. So to filter out these harmonics a filter is used at the output of the inverter.

2.2 WHY LCL-FILTER?

There are different types of filter configurations in the literature like- L, LC, LCL. The characteristics and the application of each type of filter are as follows-

2.2.1 L-Filter:

The L-filter is a first order filter having 20dB/decade attenuation over the whole frequency range. So this type of filter has its application with converters having high switching frequency where the attenuation is sufficient [5]. The L-filter topology is as shown in Fig. 2.2 and the transfer function of the L-filter is-

$$F(s) = \frac{1}{LS} \tag{2.1}$$

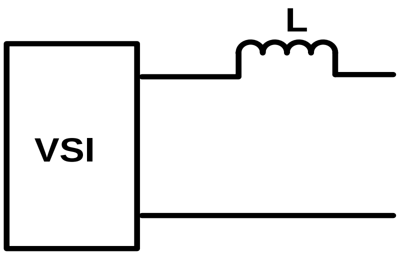


Figure2.2 PWM VSI with L-Filter

2.2.2 LC-Filter:

The LC-filter is a second order filter and has better damping characteristics than the L-filter. The LC-filter topology is as shown in Fig. 2.3 and the transfer function of the LC-filter is-

$$F(s) = \frac{SC}{LCS^2 + 1} \tag{2.2}$$

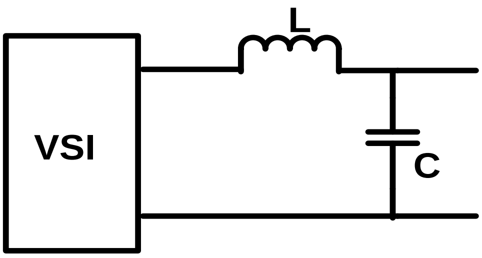


Figure2.3 PWM VSI with LC-Filter

But this filter suffers from the problem of infinite gain at resonant frequency.

2.2.3 LCL-Filter:

This is a third order filter with an attenuation of 60dB/decade above resonant frequency. So it can be used for converters with low switching frequency. It can achieve reduced levels of harmonic distortion with small value of inductance [5]. Thus, this filter suits better for the interconnection of RES with utility grid. The LCL-filter topology is as shown in Fig. 2.4.

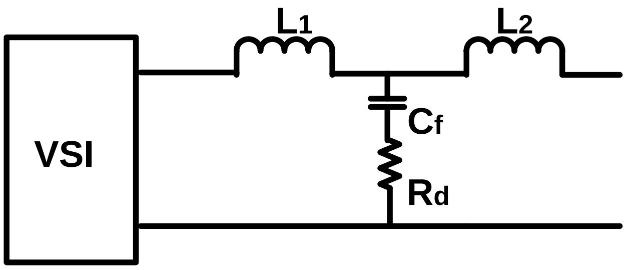


Figure2.4 PWM VSI with LCL-Filter

But this is a third order filter which is difficult to be stable and introduces resonance. So to damp out the resonance active and passive damping methods are used. The transfer function of the LCL-filter with active and passive damping methods is given by equations (2.3) and (2.4) respectively.

$$F(s) = \frac{1 + R_d S C_f}{L_1 L_2 C_f S^3 + (L_1 + L_2) R_d C_f S^2 + (L_1 + L_2) S} \qquad (2.3)$$

$$\mathrm{F(S)} = \frac{1 + \mathrm{R_d} C_f S}{\mathrm{R_d L_1 L_2 C C_f S^4 + L_1 L_2 (C + C_f) S^3} + \mathrm{R_d} C_f \mathrm{(L_1 + L_2) S^2 + (L_1 + L_2) S}} \qquad (2.4)$$

In passive damping method an additional capacitor ‘C’ is connected in parallel with filter capacitor and resistor.

The bode-plot for different filter topologies is as shown in Fig. 2.5. From the bode-plot it is clear that the LCL-filter with active damping method has better performance characteristics when compared with other filter topologies.

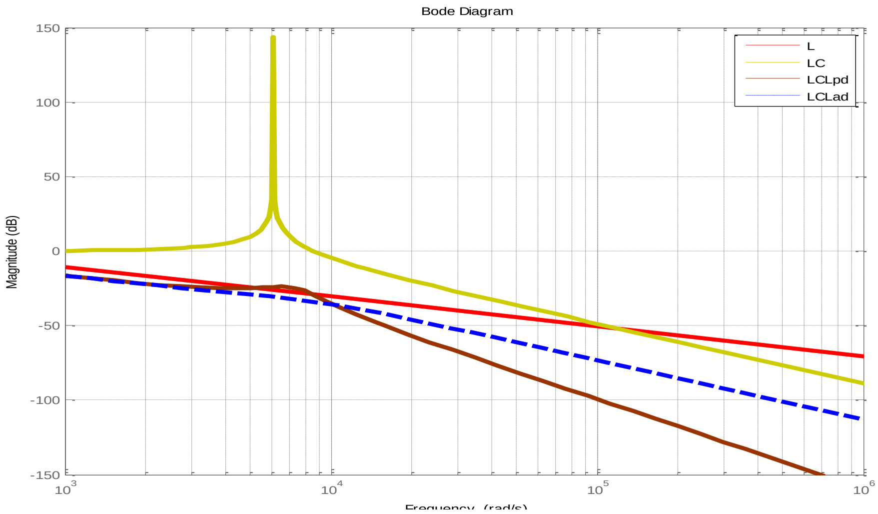


Figure2.5 Bode plot of different filter configurations

2.3 MODELING OF GRID-CONNECTED INVERTER

The mathematical model of the grid-connected RES is necessary in order to simulate and study the performance of the system at different operating conditions. There are certain assumptions based on which the mathematical model is derived [1]. They are as follows-

1. Three phase grid voltage is symmetrical, stable and internal resistance is zero
2. Three phase loop resistance and inductance are of the same value in all phases
3. Switching loss and on-state voltage drop are neglected
4. Effect of distributed parameters are neglected
5. Switching frequency of the rectifier is high enough

The circuit diagram of grid-connected inverter with LCL-filter is shown in Fig. 2.6.

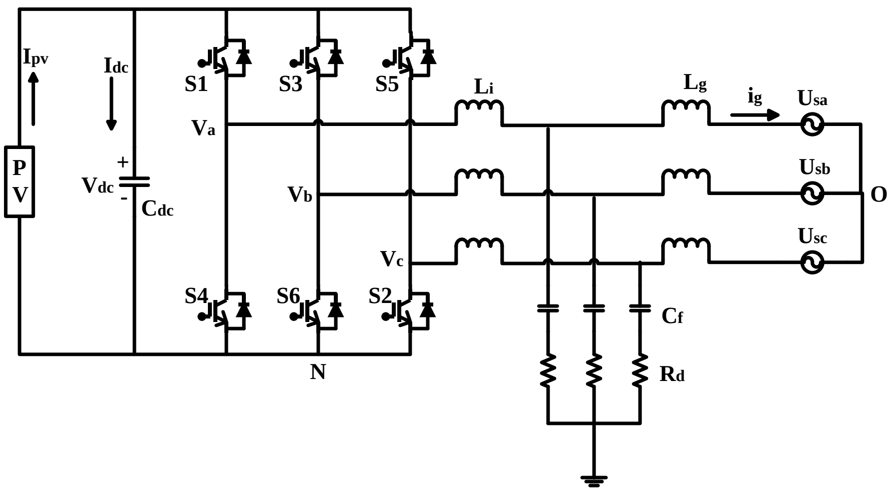


Figure2.6 Circuit-Diagram of Grid-Connected Inverter

The parameters of the Fig.2.6 are as follows:

L_i is the inverter side filter inductor

L_g is the grid side filter inductor

C_f is the filter capacitance

R_d is a small damping resistance in series with the filter capacitance

V_a , V_b , V_c are the inverter side output voltages

U_{sa} , U_{sb} , U_{sc} are the grid side output voltages

C_{dc} is the dc-link capacitance

I_{pv} is the current from the PV-panel

I_{dc} is the current through dc-link capacitor

i_i is the current from the inverter

i_g is the current entering the grid

V_{dc} is the voltage across dc-link capacitor

From the circuit diagram by using Kirchhoff Law, the voltage and current equations in stationary frame can be written as follows [6]-

$$V_{(\alpha,\beta)} = L_i \frac{di_{i(\alpha,\beta)}}{dt} + V_{C_{f(\alpha,\beta)}} \tag{2.5}$$

$$V_{C_{f(\alpha,\beta)}} = L_g \frac{di_{g(\alpha,\beta)}}{dt} + U_{s(\alpha,\beta)} \tag{2.6}$$

$$C_f \frac{dV_{C_{f(\alpha,\beta)}}}{dt} = i_{i(\alpha,\beta)} - i_{g(\alpha,\beta)} \tag{2.7}$$

Let the switching function of the inverter switches be defined as-

S_K = 1, if upper switch conducts and lower switch blocks and

= 0, if lower switch conducts and upper switch blocks

Where K=a,b,c

From Fig. 2.6 on the dc-side, $I_{pv} = I_{dc} + I_{conv}$ (2.8)

And $I_{conv} = S_a i_{sa} + S_b i_{sb} + S_c i_{sc}$ (2.9)

$$I_{dc} = C_{dc}\frac{dV_{dc}}{dt} \tag{2.10}$$

Where i_{sa}, i_{sb}, i_{sc} are the currents in phases-a,b,c respectively coming out of the inverter.

If the switching frequency is much higher than the grid voltage frequency, then the switching function, S_k can be substituted by duty cycle, d_k [1].

Thus, from equation (2.8),

$$C_{dc}\frac{dV_{dc}}{dt} = I_{pv} - (d_a i_{sa} + d_b i_{sb} + d_c i_{sc}) \tag{2.11}$$

Converting the above equation in a-b-c reference frame to stationary reference frame (αβ) using the Park's transformation matrix, the new equation obtained is-

$$C_{dc}\frac{dV_{dc}}{dt} = I_{pv} - \frac{3}{2}\left(d_\alpha i_\alpha + d_\beta i_\beta\right) \tag{2.12}$$

Where d_α, d_β are the duty ratios of the inverter switches in α-β plane and i_α, i_β are the inverter output currents in α-β plane.

2.4 CONTROL OF GRID-CONNECTED INVERTER

As said earlier, the control of the grid-side inverter is required to maintain the quality of power injected into the grid, to control active and reactive power exchange between the RES and the utility grid, to maintain dc-link voltage constant and to have grid synchronization. The control of the grid-connected inverter is based on two cascaded loops: an internal current loop and an external voltage loop [2].

The ***inner current loop*** is fast and regulates the grid current. It is responsible for power quality and current protection. It compensates the harmonics and the dynamics in the system.

The ***outer voltage loop*** is responsible for maintaining the dc-link voltage constant. It balances the power flow in the system and aims to maintain the stability of the system. Each loop is briefly described below.

2.4.1 Voltage Control Loop:

By assuming the power balance on ac and dc sides of the inverter, the transfer function of the dc-link voltage control can be obtained as-

$$G_{V_{dc}}(s) = -\frac{3}{2C_{dc}S} \tag{2.13}$$

The block diagram of the dc-link voltage controller is given in Fig. 2.7. The reference value of the dc-link voltage is compared with its actual value and the error is fed to a compensator. A gain K_{pd} is used as a compensator. The output of the compensator is added to the current feed-forward signal from the PV-panel. This is done in order to improve the dynamic response of the voltage controller in presence of rapid power changes at the PV-panel. This loop generates the active current reference value for the inner current loop. The value of gain K_{pd} is calculated to obtain a 50 Hz bandwidth [2].

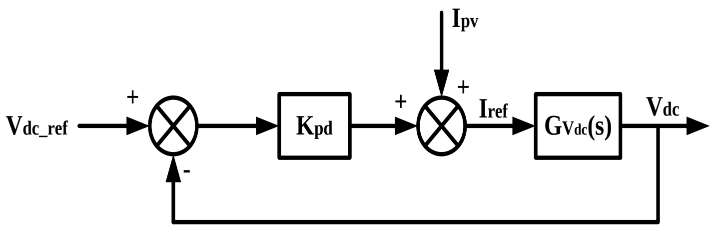


Figure2.7 DC-link Voltage Loop Control

2.4.2 Current Control Loop:

The current controller of three-phase VSI plays an indispensable role in controlling grid-interfaced inverter. Consequently, the quality of the applied current controller largely influences the performance of the inverter system. Many control mechanisms have been proposed to regulate the inverter output current that is injected into the utility grid.

The current control techniques are of two types-linear and non-linear [22]. The classification of the current control techniques is shown in Fig. 2.8.

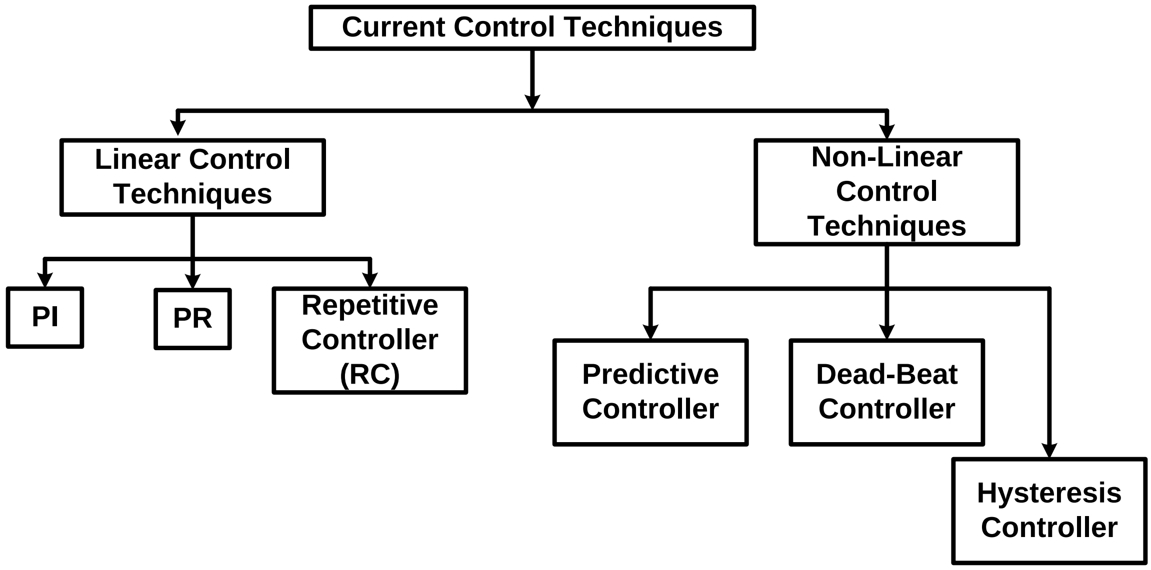


Figure2.8 Classification of Current Control Techniques

Non-linear controllers have good dynamic response but introduce a time delay. So linear control techniques are preferred mostly. Among the linear current control techniques PI and PR are most commonly used.

A. Proportional-Integral (PI) Controller:

It contains a proportional gain K_p and an integrator with gain K_I. The integral component helps in eliminating the steady state error. The transfer function of the PI controller is-

$$G_{PI}(s) = K_p + \frac{K_I}{S} \tag{2.14}$$

The proportional and integral gain values are calculated by Symmetrical Optimum Method [24]. Even though the current error turns to zero in steady state, it may appear in transient condition. This controller is mainly used in d-q reference frame where the grid voltage and currents are dc variables. In d-q reference frame, the current equations are given as [1]-

$$L_s \frac{di_d}{dt} - \omega L_s i_q = V_{dc} d_d - U_m \tag{2.15}$$

$$L_s \frac{di_q}{dt} + \omega L_s i_d = V_{dc} d_q \tag{2.16}$$

Where L_s is the grid-inductance and U_m is the maximum value of grid voltage. From above equations it is clear that the system is strongly coupled and the design complexity increases. So to reduce the complexity, the control is done in stationary reference frame (α-β). In stationary reference control the advantage is that the number of control variables is reduced. But in stationary reference frame control, the control variables are sinusoidal in nature. So PI controllers fail in removing the steady state error. As a consequence employment of other type of controllers is necessary. Due this drawback a new controller known as proportional resonant (PR) controller gains large popularity in current regulation for grid connected inverter system.

B. Proportional-Resonant (PR) Controller:

To overcome the drawback of the PI controller, PR controllers are proposed. The advantage of PR controller is the possibility of implementing harmonic compensator without affecting the controller dynamics [3]. The transfer function of an ideal PR controller is-

$$G_{PR}(s) = K_p + \frac{2K_i s}{s^2 + \omega^2} \tag{2.17}$$

But this has an infinite gain at the frequency ω rad/s. So a cut-off frequency ω_c is introduced to obtain finite gain and also to reduce sensitivity towards utility grid frequency variations by adjusting the band-width. Thus, the transfer function of non-ideal PR controller is-

$$G_{PR}(s) = K_p + \frac{2K_i \omega_c s}{s^2 + 2\omega_c s + \omega^2} \tag{2.18}$$

With the flexibility of tuning the resonant frequency, the PR controller can be used for selectively compensating the low-order harmonics. The gain values are calculated by using the formulae give in [4].

2.4.3 Control Strategy:

The main aim of the control strategy is to obtain unity power factor operation and to reduce the harmonics in the current injected into the grid. To achieve these objectives, the grid voltage is aligned along the d-axis of the 2-ϕ rotating coordinates. So $V_d = V_g$ and $V_q = 0$.

The grid voltage and current when expressed in d-q reference frame can be written as-

$$V_g = V_d + jV_q \tag{2.19}$$

$$I_g = I_d + jI_q \tag{2.20}$$

Three-phase complex power injected to the grid is given as-

$$S = V.I^* \tag{2.21}$$

Thus, the complex power in d-q reference frame is given as-

$$S = V_d I_d - jV_d I_q \tag{2.22}$$

This shows that active power injected to the grid depend on ‘I_d’ and reactive power depends on ‘I_q’. Thus, the active and reactive powers are controlled independently. To make the reactive power exchange to zero, the reference value I_q^* is set to zero. The current I_d is controlled to meet the active power demand. So its reference value is calculated from (2.22) as-

$$I_d^* = \frac{P^*}{V_d} = \frac{P^*}{V_g} \tag{2.23}$$

Where P^* is the reference power.

These reference currents are transformed to α-β plane and compared with their actual values. The error is then passed through a PR-controller and finally pulses are generated for inverter switches.

2.5 CHAPTER SUMMARY

This chapter deals with different filter topologies for grid interconnection. It also provides the mathematical modeling of the grid connected RES with an LCL-filter. The various control techniques used for controlling the grid-connected inverter are also discussed. The basic idea of the control strategy is also presented in this chapter.

CHAPTER 3

ACTIVE AND PASSIVE DAMPING METHODS

3.1 INTRODUCTION

The LCL-filter has many advantages and suits best for grid interconnection of RES. But it may cause resonance with the grid impedance and may affect the stability of the system. In order to ensure stable operation of the utility grid, the filter resonance should be damped out effectively. This chapter explains active and passive damping methods for mitigating the resonance problem.

3.2 ACTIVE DAMPING

The active damping technique is a type of control algorithm other than physical elements [8]. It may use full state feedback, voltage or current feedback of the LCL filter capacitor or inductor, delay in the control circuit etc. The basic circuit diagram of LCL filter is shown in Fig. 3.1. Here a small resistance R_d is used in series with the filter capacitor to provide the damping if the active damping control fails. Each type of active damping method is described below.

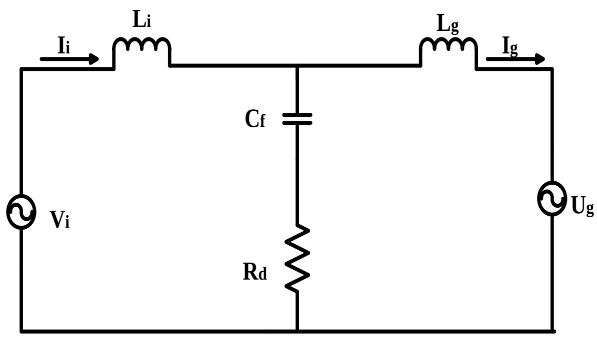


Figure3.1 Circuit Diagram of LCL-Filter

3.2.1 Full-state Feedback:

According to the modern control theory, the system could be stabilized with the feedback of all state variables such that the closed-loop system poles are located in the stability region. The system has good static and dynamic performance with the allocation of closed loop system poles in the desired region, but it is analog control. So a full-state feedback current control method has been proposed in [8], which assigns the poles in the Z domain, but it is sensitive to the system parameters. It requires more number of sensors and increases the cost and complexity. The full state feedback has limited control bandwidth and larger phase lag. It requires the support of other control algorithms to achieve good performance. Thus, it is not used widely.

3.2.2 Capacitor Voltage or Current Feedback:

Capacitor current feedback is a typical method of virtual damping. It achieves the same function as a passive damping resistance. The feedback capacitor voltage method is the deformation of feedback capacitor current method. This method needs a lead-lag network to compensate the shift in the phase angle introduced by the filter and to stabilize the system [14].

3.2.3 Notch Filter:

This method consists of adding a filter in series with the reference voltage of the modulator. The basic idea is to introduce a negative peak (notch) in the system that compensates the resonant peak caused by the LCL filter [17]. For this the notch filter is added in the current loop. The frequency of the notch filter has to be tuned at the resonance frequency of the LCL filter in order to provide good damping.

3.2.4 Filter Inductor Current Feedback:

A control algorithm with filter inductor current feedback can also be considered. It can be either inverter side inductor current feedback or grid side inductor current feedback. The control strategy implemented in this project considers the inverter side inductor current feedback. The three phase inverter current is converted into 2-ϕ stationary reference frame (α-β). These currents are then compared with their reference values and the error is then passed through the PR controller. The output of the PR controller is added with feed forward grid voltage to reduce the harmonics in the grid current injected [3]. It also keeps the control algorithm in track with the changes in grid voltage. Then the signals are passed through a PWM generator to generate the pulses to the inverter switches. The overall control block diagram is shown in Fig. 3.2.

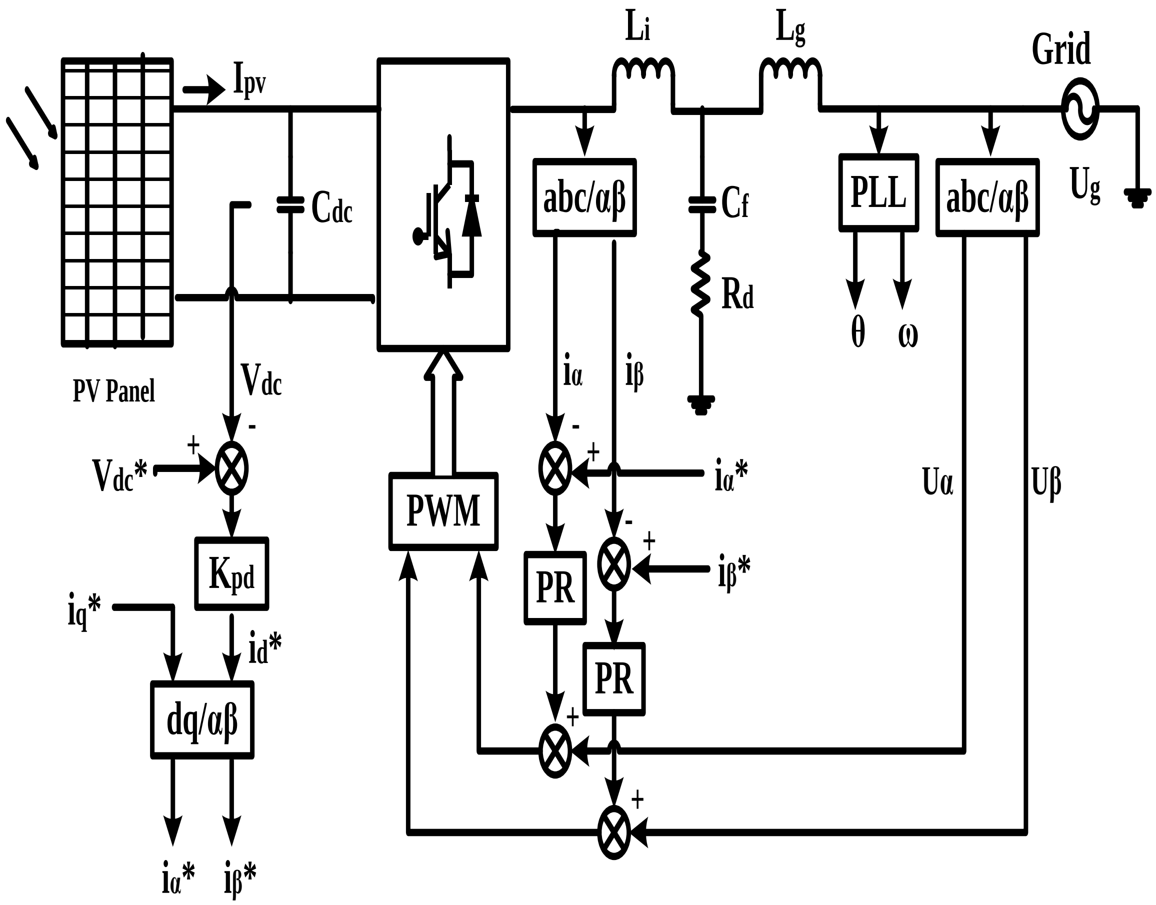


Figure3.2 Overall Control Strategy of Grid-connected PWM VSI

3.3 PASSIVE DAMPING

Passive damping methods usually use physical resistors. The resistor can be connected either in series with or in parallel with the inductor or capacitor of the filter. As it is simple and easy to realize, it is widely used. Other passive elements such as inductor, capacitor can also be connected in addition to the resistors. There are many passive filter topologies in the literature [8] like- an inductor shunting the damping resistance, a capacitor connected in parallel with the filter capacitor and damping resistor, a parallel LC resonant circuit shunting the damping resistor etc. But in this method the losses are more so the efficiency is reduced. Thus, this method finds application where cost should be less and efficiency can be sacrificed slightly.

In this project a passive damping method where an additional capacitor is connected in shunt with the filter capacitor and damping resistor is used [13]. The filter circuit is shown in Fig. 3.3.

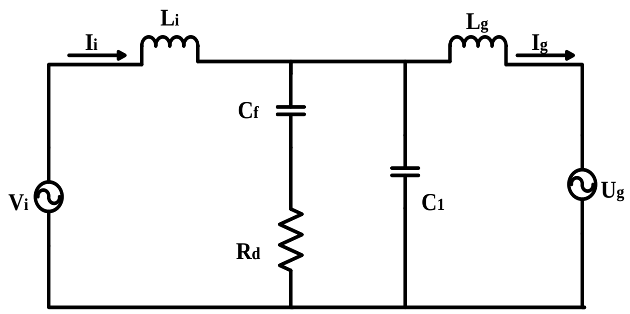


Figure3.3 Passive Damping Configuration of LCL-filter

3.4 SIMUALTION RESULTS

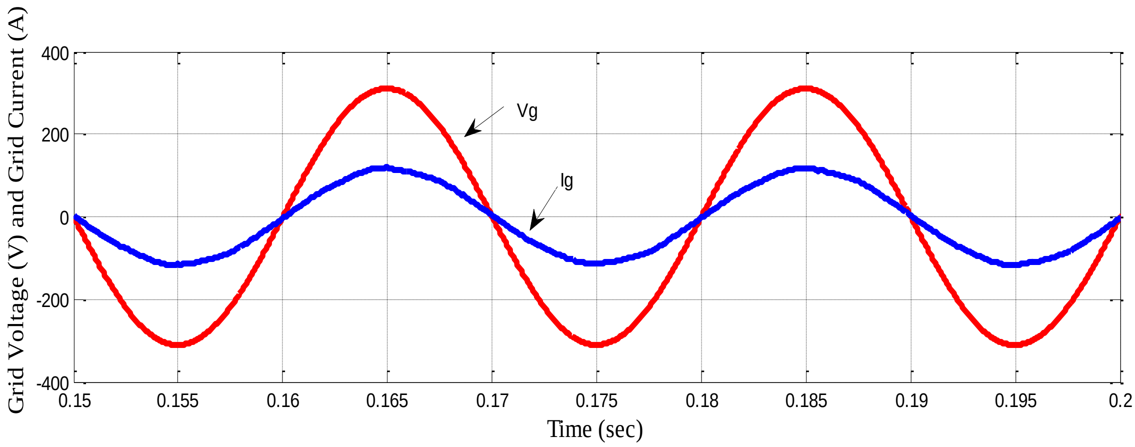
The overall control strategy of grid-interfaced inverter with active and passive damping methods for LCL-type filter configuration is studied and analyzed using MATLAB-Simulink environment. The system parameters considered for this study are given in Table-1. The obtained results during steady state and transient conditions are discussed in this section.

TABLE-I. SYSTEM PARAMETERS

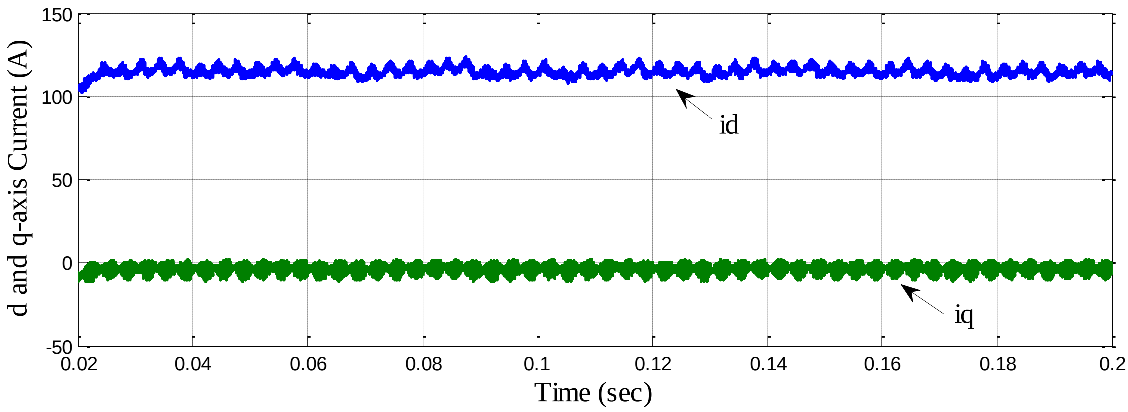
Symbol	***Parameter***	***Value***
P_{pv}	System power	100 kW
V_{dc}	DC-link voltage	600 V
U_g	Grid voltage	380 V (line-to-line)
C_{dc}	DC-link capacitance	13400 µF
f_s	Switching frequency	4.5 kHz
L_i	Inverter side inductance	2 mH
L_g	Grid side inductance	1.8 mH
C_f	Filter capacitance	4.7 µF
R_d	Damping resistor	2.2 Ω
C_1	Damping capacitor	4.7 µF

3.4.1 During Steady State Conditions:

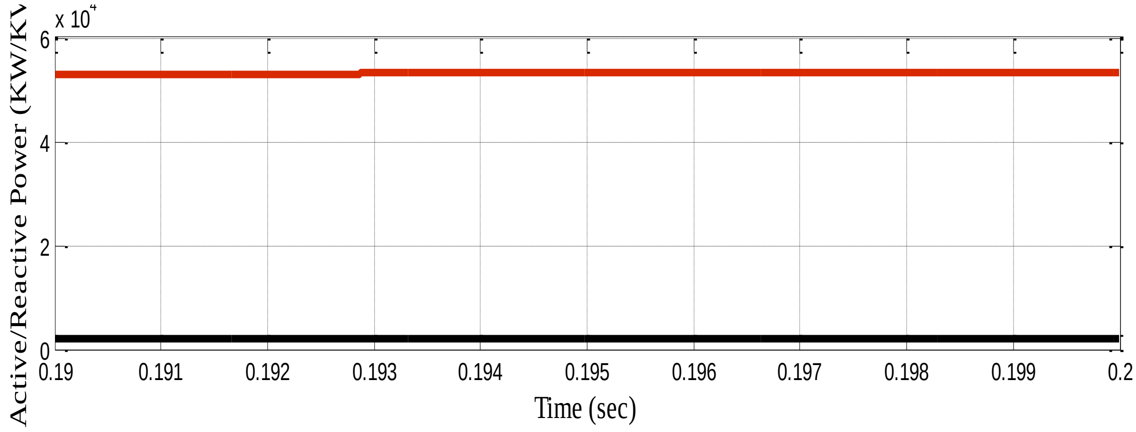
The simulation results under steady-state condition for active and passive damping methods are illustrated in Fig. 3.4 and Fig. 3.5 respectively. Fig.3.4 (a) shows the three-phase grid voltage and grid current waveforms under steady state conditions using active damping method and they are almost close to sinusoidal waveforms. Fig.3.4 (b) depicts d and q-axis grid current components and q-axis component is almost zero. And it implies that there is no reactive power injected into the grid and it ensures unity power factor operation of the grid. The corresponding grid active and reactive power response is shown in Fig.3.4 (c). Also the dc-link voltage is maintained constant at 600 V which is illustrated in Fig.3.4 (d). With the help of active damping method, PWM VSI with LCL filter injects sinusoidal current into the grid. As a result, THD of grid current is largely reduced (1.66%) and it is shown in Fig.3.4 (e). The corresponding steady state response of passive damping method for LCL-type filter for grid-connected PMW VSI is shown in Fig. 3.5.



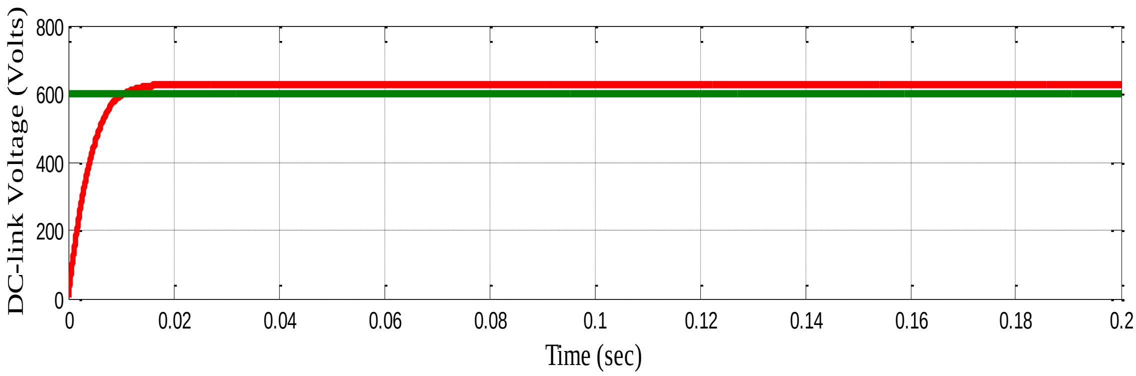
(a)



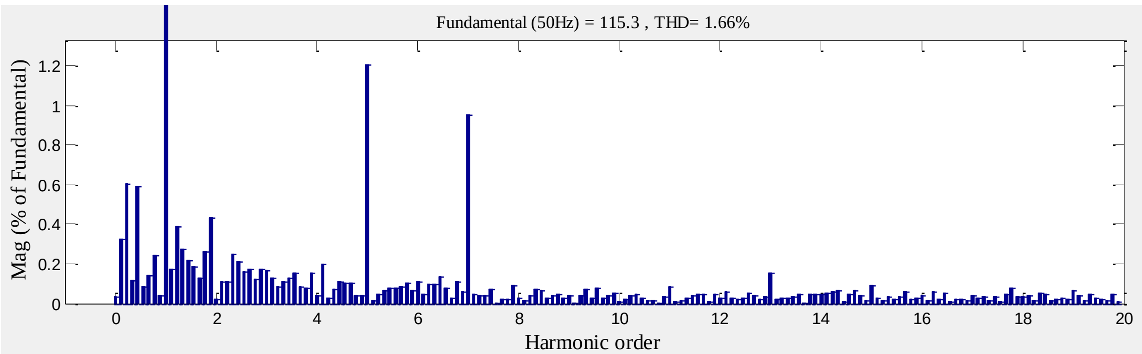
(b)



(c)

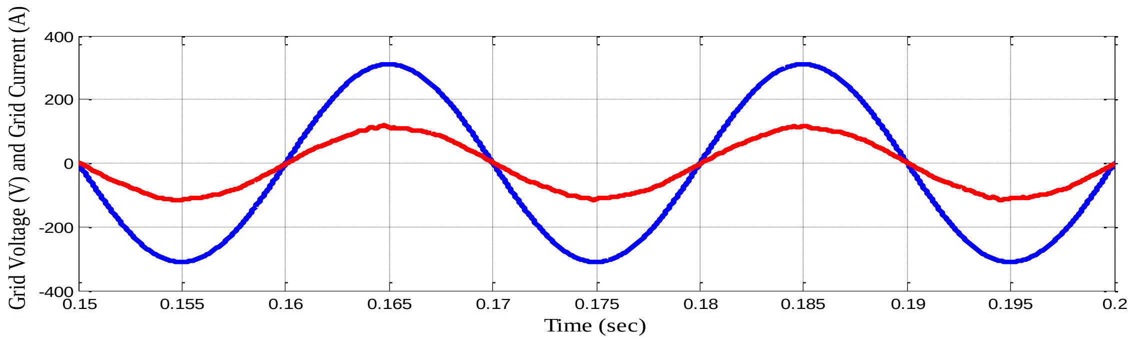


(d)

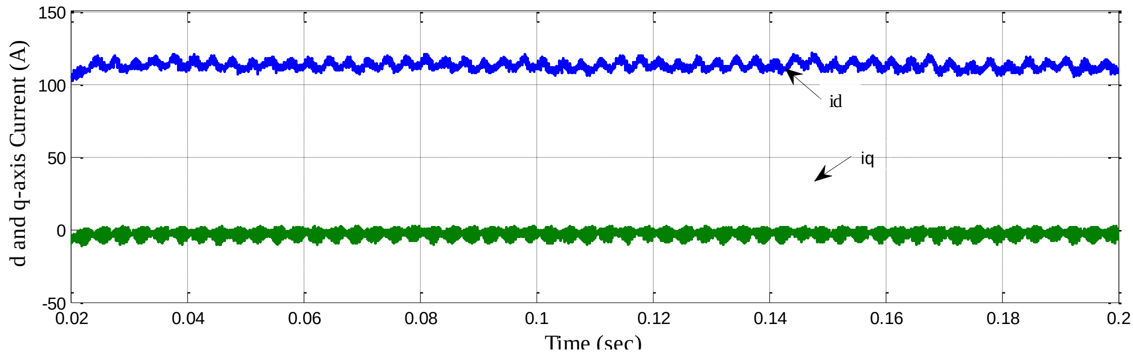


(e)

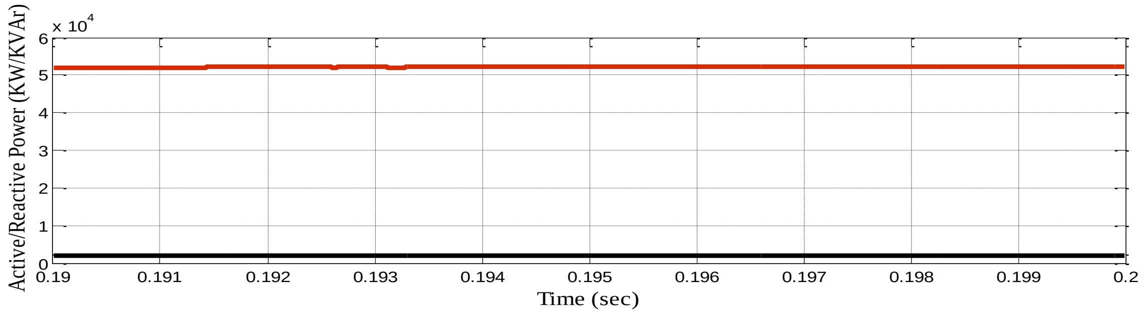
Figure3.4 Simulation results for active damping method under steady state condition (a) Grid voltage and grid Current waveforms (b) d and q-axis grid currents (c) Response of active and reactive Power (d) Response of dc-link voltage (e) THD of grid current.


Grid Voltage (V) and Grid Current (A)
Time (sec)

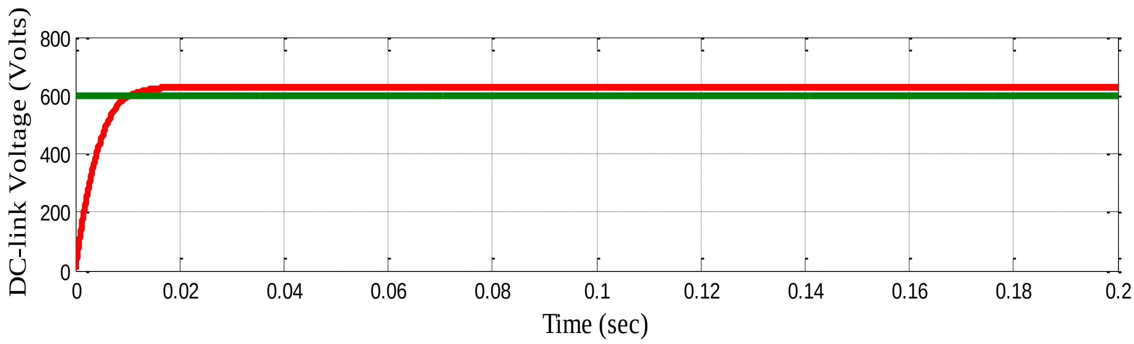
(a)


d and q-axis Current (A)
id
iq
Time (sec)

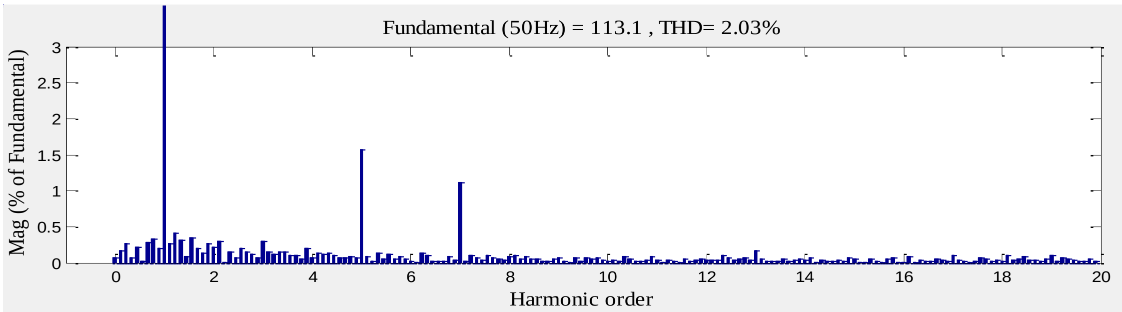
(b)


x 10^4
Active/Reactive Power (KW/KVAr)
Time (sec)

(c)


DC-link Voltage (Volts)
Time (sec)

(d)

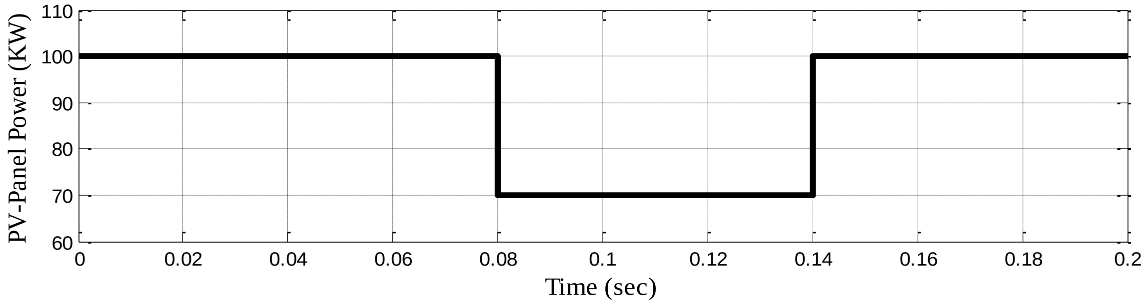


(e)

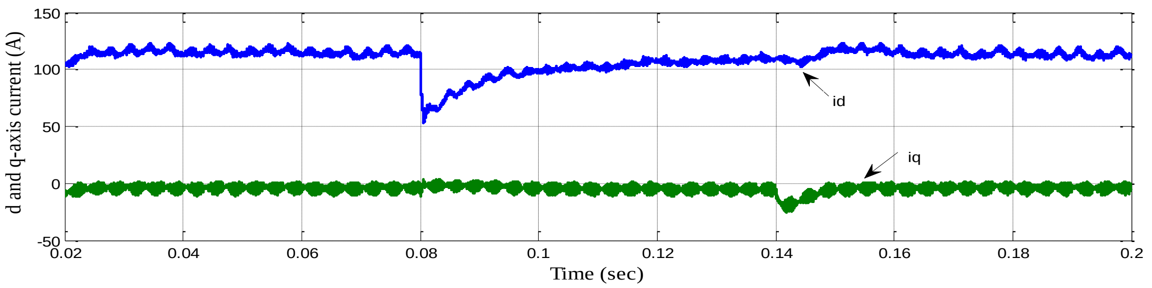
Figure3.5 Simulation results for passive damping method under steady state condition (a) Grid voltage and grid Current waveforms (b) d and q-axis grid currents (c) Response of active and reactive Power (d) Response of dc-link voltage (e) THD of grid current.

3.4.2 During Step Change in the Input PV power:

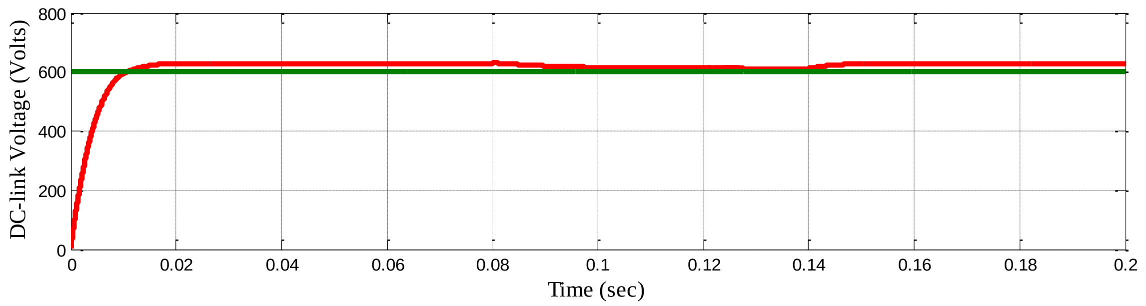
In order to simulate the operation of the proposed control strategy and to analyze the transient response of both active and passive damping method of LCL-type filter, a step changes in the extracted PV power whose amplitude reduced from 100 kW to 70 kW at 0.08 sec is applied and the related simulation results are shown in Fig.3.6 and Fig.3.7 respectively. Due to step change in the PV power input at 0.08 sec, d-axis grid current component is changed at 0.08 sec and it reaches the steady state at 0.1 sec which is clearly shown in Fig.3.6 (b). However, q-axis grid component is still zero because of the proposed control strategy and it ensures unity power factor operation of the grid. This figure shows that after a small transient time, the output inverter current reaches its steady state value of 100 A, which is exactly equal to the reference value. This proves that the current loop controller along with active damping method in the LCL-type filter is effective such that measured currents track their references with constant dc-link voltage of 600 V (from the Fig.3.6 (c)). Moreover, its dynamic behavior is satisfactory. In addition, the active damping method with LCL-type filter injects sinusoidal current into the grid with lesser THD (1.85% from the Fig.3.6 (d)). The corresponding response of passive damping method with LCL-type filter for grid-connected PWM VSI is illustrated in Fig.3.7.



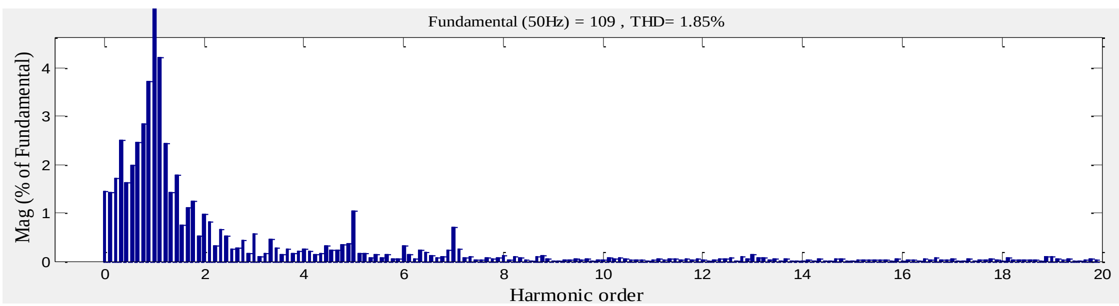
(a)



(b)

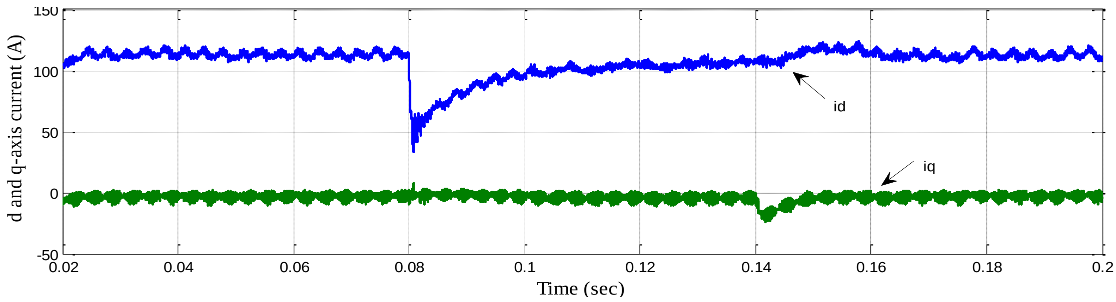


(c)

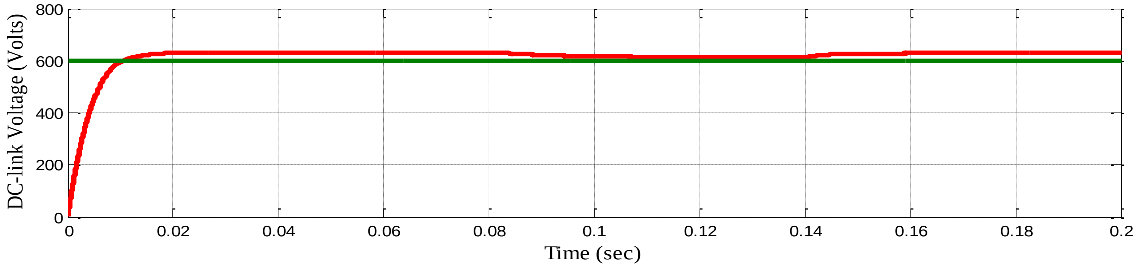


(d)

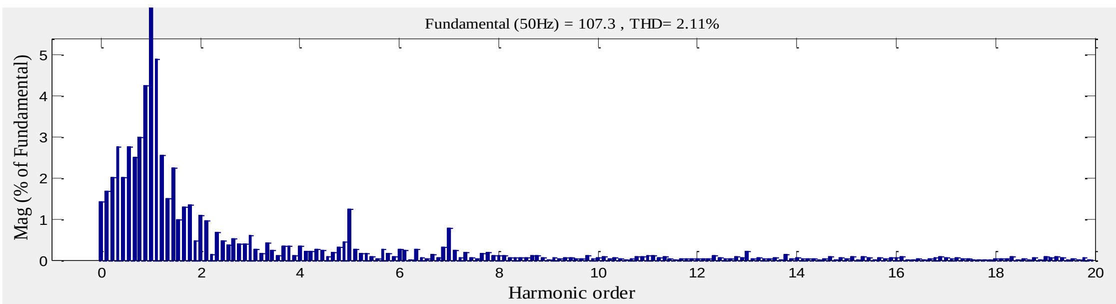
Figure3.6 Simulation results for active damping method during step change in the input PV power (a) Step change in the input PV power (b) d and q-axis grid currents (c) Response of dc-link voltage (d) THD of grid current.



(a)



(b)



(c)

Figure3.7 Simulation results for passive damping method during step change in the input PV power (a) d and q-axis grid currents (b) Response of dc-link voltage (c) THD of grid current.

3.4.3 Comparative Analysis:

A comparative study between active and passive damping methods for LCL-type filter is discussed here. With reference to Table-II, it is found that, the active damping method is superior over passive damping method and it ensures almost sinusoidal current injection into the grid with reduced THD. Also the loss befalling in the passive damping method are more with the introduction of extra physical components, which further reduces the overall efficiency of grid-connected inverter system.

TABLE-II. THD OF GRID CURRENT COMPARISON

Type of Damping	Steady-State Condition	Source Dynamics Condition
Active Damping	1.66%	1.85%
Passive Damping	2.03%	2.11%

3.5 CHAPTER SUMMARY

This chapter discusses the active and passive damping methods to damp out the LCL filter resonance. The proposed control strategy is simulated in MATLAB-SIMULINK environment. In addition, a comparative study has been made between active and passive damping methods. From the above said discussions, it is found that active damping method is better than passive damping method to inject sinusoidal current into the grid with less THD. Also it ensures zero steady state error with stable response. In addition to that, passive damping method involves extra cost and losses due to additional circuit components. Nevertheless, active damping method difficult to implement, but overall performance of grid-connected PWM VSI is improved with higher efficiency.

CHAPTER 4

CONTROL STRATEGY TO REDUCE LOW-ORDER HARMONICS

4.1 INTRODUCTION

The RES are connected to the utility grid through a power electronic converter. The output of the converter contains harmonics which should be filtered before injecting to the grid. The series connected LCL filter serves this purpose. With the series LCL filter, the THD is greatly reduced but the lower order harmonics are prominent. In order to reduce these harmonics and increase the amount of current injected into the grid, there is another topology of filter in the literature [12]- *shunt connected LCL filter*. This filter reduces the THD more than the series LCL filter and increases the amount of current injected into the grid. This chapter deals the control of grid connected inverter with shunt connected LCL filter.

4.2 SHUNT CONNECTED LCL FILTER

The shunt connected LCL filter is a slight modification of the series LCL filter. Here the filter is connected in shunt at the Point of Common Coupling (PCC). The block diagram of the shunt connected LCL filter for a 1-ϕ system is shown in Fig. 4.1. In the Fig. 4.1 L_1, L_2 and C constitute the LCL filter. The grid inductance is represented by L_g. The voltage source V_i represent the output voltage of the inverter and the voltage source U_g represent the grid voltage. The filter inductor may contain some parasitic resistance values when preferring a low-cost solution [12].

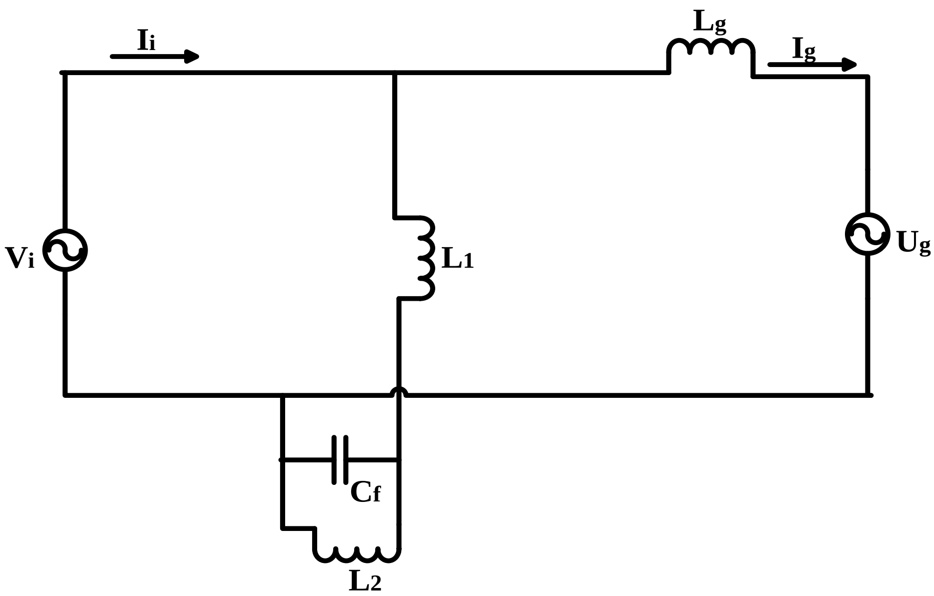


Figure4.1 Block Diagram of Shunt Connected LCL Filter

4.3 CONTROL OF GRID CONNECTED INVERTER

The control strategy for grid connected inverter with shunt connected LCL filter is same as that of the series LCL filter except that it involves the calculation of the compensation current, which compensates the low-order harmonics. The overall control block diagram is shown in Fig. 4.2. In the figure, L_1, R_1; L_2, R_2 and C_f constitute the shunt LCL filter. The inductor, L_2, current is sensed to calculate the compensation current. The whole control is done in 2-ϕ stationary (α-β) reference frame.

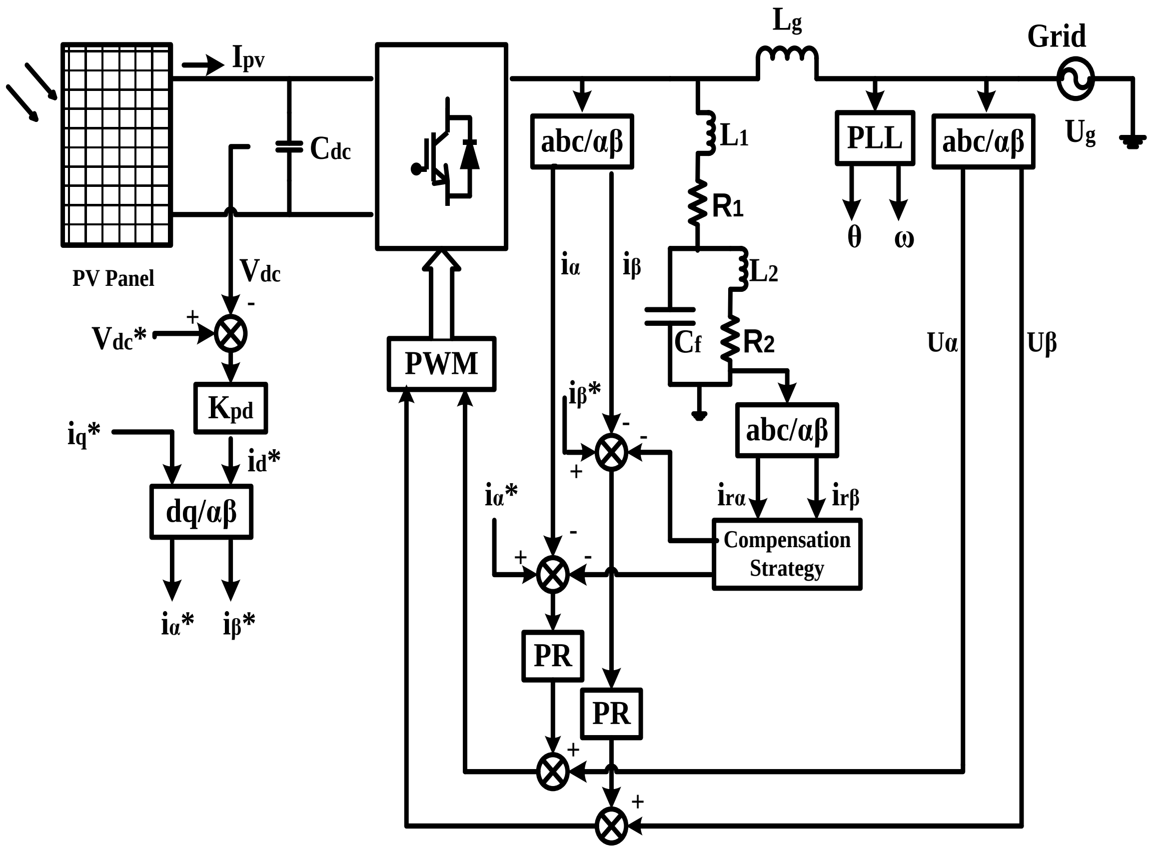


Figure4.2 Control Block Diagram with Shunt Connected LCL-Filter

4.3.1 Compensation Strategy:

In grid connected power converters usually a line frequency transformer is usually employed either in traditional or in renewable energy sources. This is usually employed in order to suppress the DC component. But in the recent solutions is transformer less architecture in order to reduce size, weight and cost. The exclusion of line frequency transformer leads to the presence of DC component at the output of the power converter. Thus, the DC component along with other low frequency harmonics reduces the quality of current injected to the grid. Therefore, in transformer less architecture the power converter should be controlled in such a way that the DC component is eliminated from converter output and the performance of the system is enhanced.

The main idea behind the control strategy is that- the reactor current distorts due to the presence of DC component and the distortion may occurs either in the positive half cycle or in the negative half cycle of the current waveform. To detect this distortion, for every grid voltage period two indices are computed [12]. They are *Positive Saturation Index (SI_P)* and *Negative Saturation Index (SI_N).* These indices are computed by integrating the reactor current in suitably small time gap placed around the zero crossing of grid voltage. The difference between SI_P and SI_N is the input to the PI controller. The output of the PI controller is the compensation current that dynamically compensates the grid offset and the low-order harmonics. If there is no distortion then both SI_P and SI_N will be equal and the input to PI controller is zero. Then there is no generation of compensation current and the control algorithm works normally generating triggering pulses to the inverter switches. The block diagram of the compensation strategy is shown in Fig. 4.3.

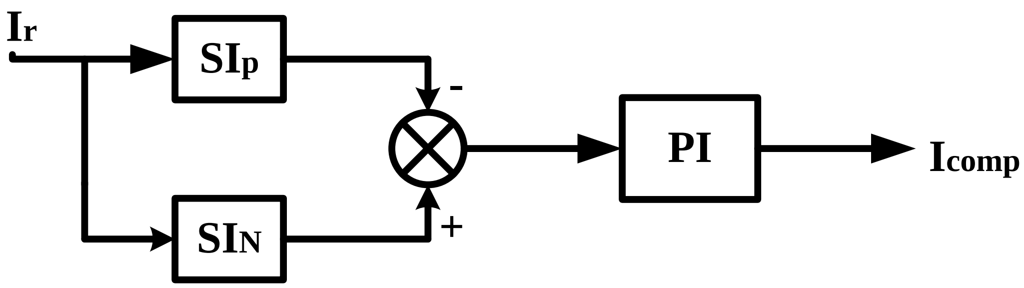


Figure4.3 Block Diagram of Compensation Strategy

4.4 SIMULATION RESULTS

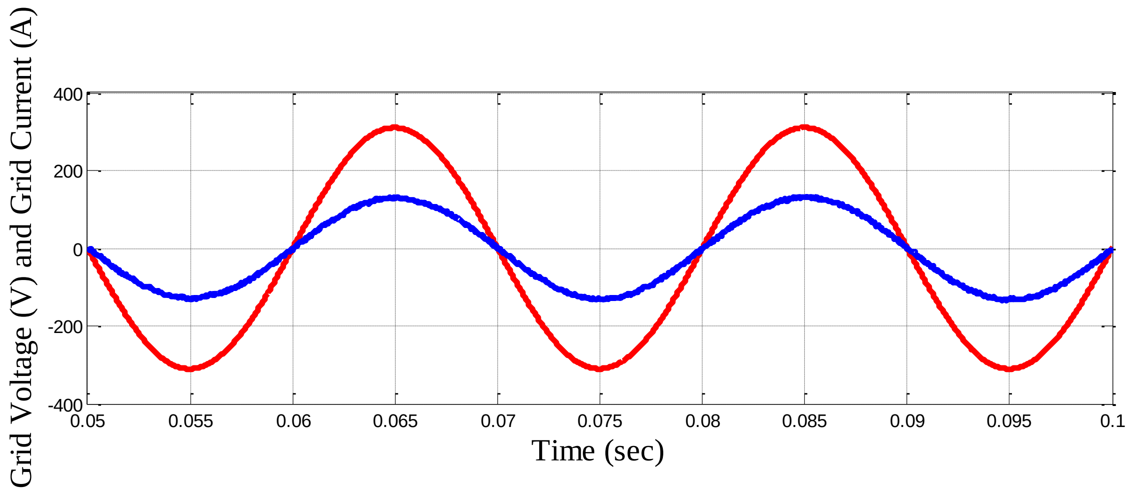
The proposed control strategy is simulated in MATLAB SIMULINK environment and the results are discussed in this section. The parameter values of the shunt connected LCL filter are given in Table-III.

TABLE-III. SYSTEM PARAMETERS

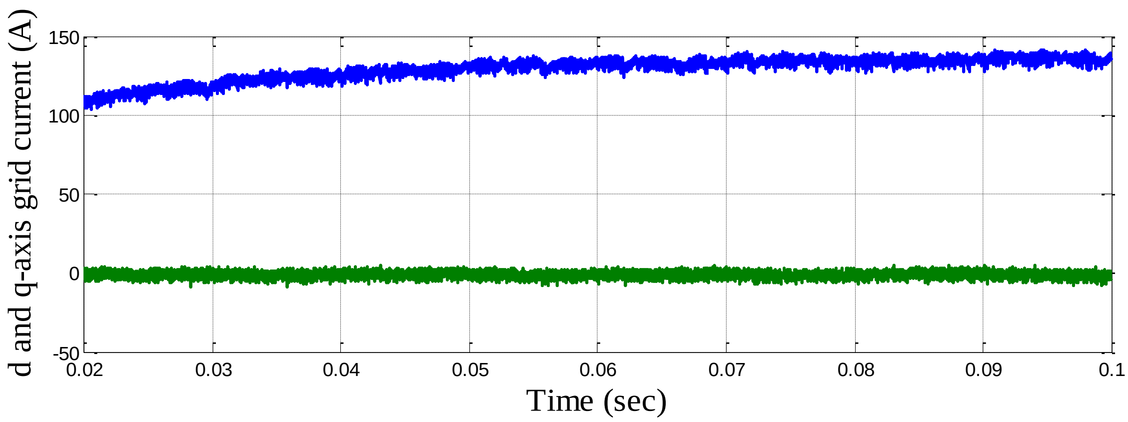
Symbol	*Parameter*	*Value*
P_{pv}	System power	100 kW
V_{dc}	DC-link voltage	600 V
U_g	Grid voltage	380 V (line-to-line)
C_{dc}	DC-link capacitance	13400 µF
f_s	Switching frequency	4.5 kHz
L_1	LCL Filter Inductance	1.2 mH
L_2	LCL Filter Inductance	1.1 mH
L_g	Grid inductance	1.8 mH
C_f	Filter capacitance	1.5 µF
R_1	Filter resistor	29 Ω
R_2	Filter resistor	54 Ω

4.4.1 During Steady State Conditions:

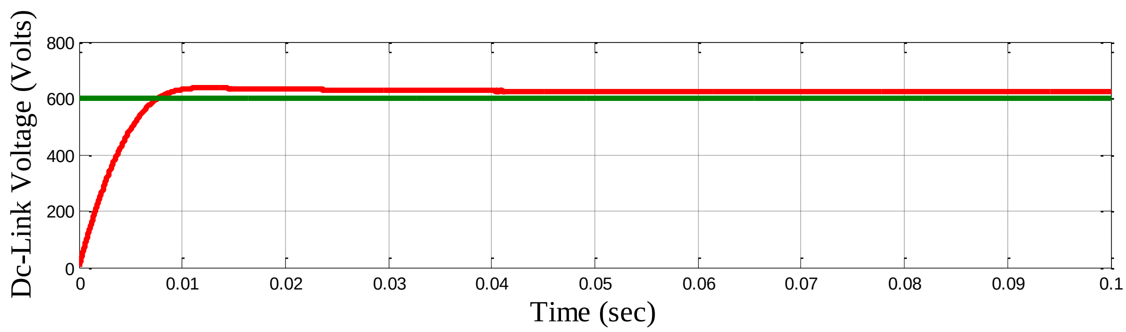
The simulation results under steady-state condition are illustrated in Fig. 4.4. Fig.4.4 (a) shows the three-phase grid voltage and grid current waveforms under steady state conditions and they are almost close to sinusoidal waveforms. Fig.4.4 (b) depicts d and q-axis grid current components and q-axis component is almost zero. And it implies that there is no reactive power injected into the grid and it ensures unity power factor operation of the grid. Also the dc-link voltage is maintained constant at 600 V which is illustrated in Fig.4.4 (c). The THD of grid current is largely reduced (1.27%) when compared with series connected LCL-filter and it is shown in Fig.4.4 (d). Thus, the fundamental component of the current injected to the grid has been increased, increasing the active power supplied by the RES to the utility grid.


Grid Voltage (V) and Grid Current (A)
400
200
0
-200
-400
0.05
0.055
0.06
0.065
0.07
0.075
0.08
0.085
0.09
0.095
0.1
Time (sec)

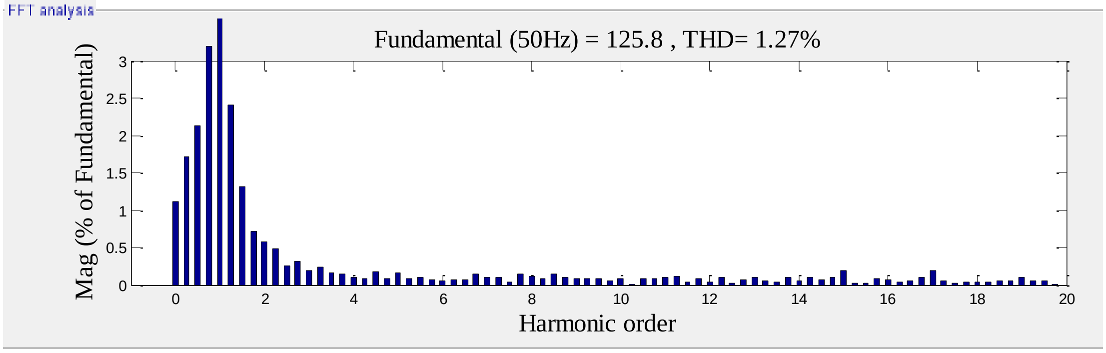
(a)


d and q-axis grid current (A)
150
100
50
0
-50
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time (sec)

(b)


Dc-Link Voltage (Volts)
800
600
400
200
0
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time (sec)

(c)

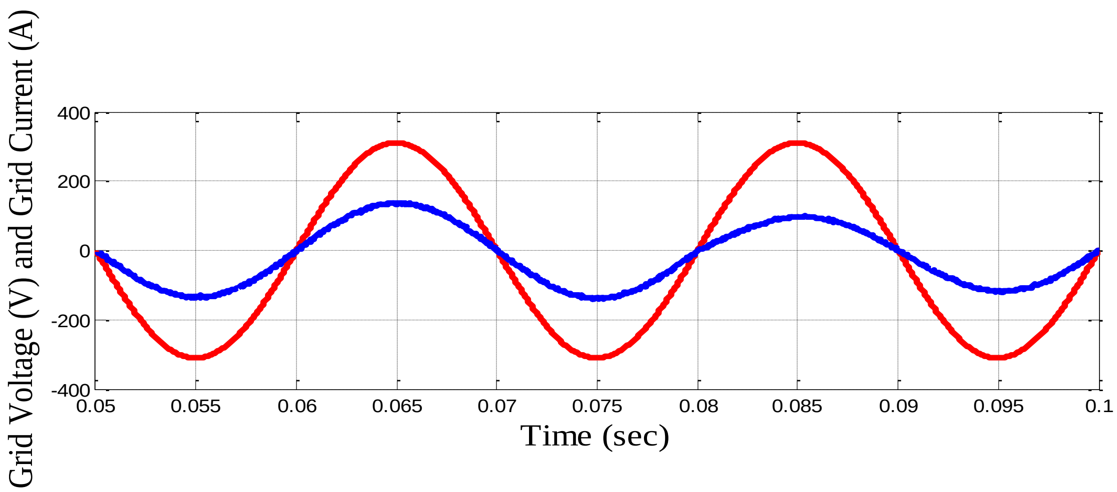


(d)

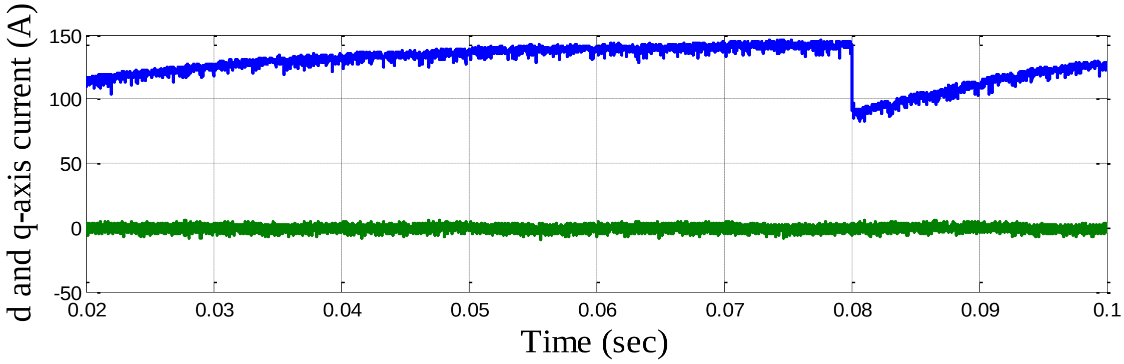
Figure4.4 Simulation results under steady state condition (a) Grid voltage and grid Current waveforms (b) d and q-axis grid currents (c) Response of DC-link voltage (d) THD of grid current.

4.4.2 During Step Changes in the Input PV power:

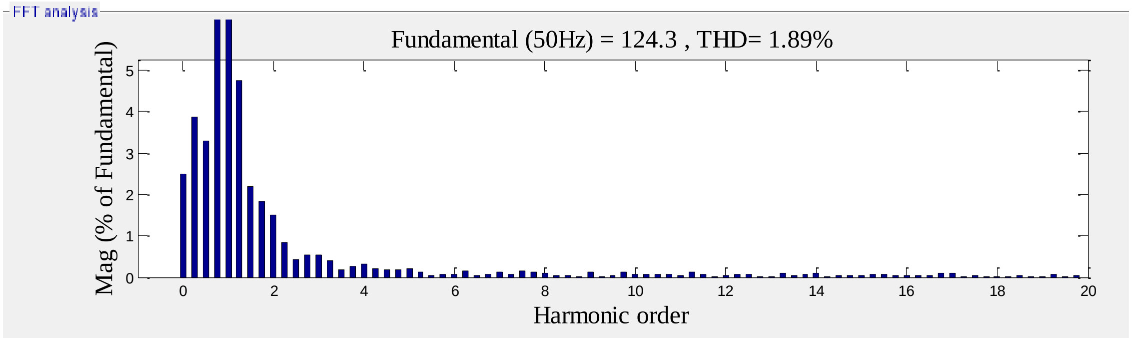
In order to simulate the operation of the proposed control strategy and to analyze the transient response of shunt connected LCL-type filter, a step changes in the extracted PV power whose amplitude reduced from 100 kW to 70 kW at 0.08 sec is applied and the related simulation results are shown in Fig.4.5. Due to step change in the PV power input at 0.08 sec, d-axis grid current component is changed at 0.08 sec and it reaches the steady state at 0.1 sec which is clearly shown in Fig.4.5 (b). However, q-axis grid component is still zero because of the proposed control strategy and it ensures unity power factor operation of the grid. In addition, the shunt connected LCL-type filter injects sinusoidal current into the grid with lesser THD (1.89% from the Fig.4.5 (c)) even in transient conditions. As in steady state condition, the amount of current injected into the grid has been increased when compared to series connected filter.



(a)



(b)



(c)

Figure4.5 Simulation results under step changes in input PV power (a) Grid voltage and grid Current waveforms (b) d and q-axis grid currents (c) THD of grid current.

4.4.3 Comparative Analysis:

A comparative study between series and shunt connected LCL-type filter is discussed here. With reference to Table-IV, it is found that, the shunt connected LCL filter is superior over series connected filter and it ensures almost sinusoidal current injection into the grid with reduced THD increasing the fundamental component of the injected grid current.

TABLE-IV. COMPARISON OF SERIES AND SHUNT CONNECTED LCL FILTER

	Steady State Condition		*Source Dynamics Condition*	
	Series LCL	**Shunt LCL**	**Series LCL**	**Shunt LCL**
Overall THD of Grid Current	1.75%	1.27%	2.36%	1.89%
Fundamental Grid Current (A rms)	81.61 A	88.97 A	76.42 A	87.88 A

4.5 CHAPTER SUMMARY

This chapter deals with the shunt connected LCL filter. It explains the control strategy of the grid connected inverter with shunt LCL filter and presents the MATLAB simulations results of the proposed control strategy. From the simulation results it is clear that the shunt connected LCL filter has better performance for grid interconnection application. Finally a comparative study is made between series and shunt connected filters, which shows that the shunt filter increases the fundamental component of the injected grid current thereby increasing the amount of active power injected by the RES.

CHAPTER 5

CONCLUSIONS

5.1 CONCLUSIONS

Now-a-days, the integration of renewable energy sources to the grid is one of the most discussed topics in power industry. There are numerous issues and challenges regarding grid interconnection.

The harmonics present in the injected grid current is one of the major issues. To overcome these problems, LCL filter can be used which filters the harmonics. But it suffers from the resonance problem. In order to overcome these problems, active and passive damping methods have been proposed in this project. And also the control of grid connected inverter with LCL filter is studied and analyzed.

Following work carried out in this project-

- The grid connected RES system has been presented
- The use of filter for grid interconnection and the advantage of LCL filter has been explained
- The mathematical model of the grid connected RES with LCL filter has been derived
- The basic control strategy of grid connected inverter has been explained
- Active and passive damping methods to damp out filter resonance have been proposed
- A comparative study of two different filter topologies has been made

By using the MATLAB-SIMULINK the following simulations were done-

- Simulation of 3-ϕ grid connected RES with series LCL filter using active and passive damping methods under steady state and source dynamics conditions and it has been found that active damping method has better response with reduced grid current THD
- Simulation of 3-ϕ grid connected RES with shunt LCL filter under steady state and source dynamics conditions. From this simulation it is found that the shunt LCL filter has better characteristics and suits better for grid interconnection as it increases the fundamental grid current injected by the RES

From this project the following conclusions are made-

- Among the different filter topologies present in the literature, the LCL filter best suits for grid interconnection application
- The active damping method of LCL filter has better response with reduced THD of grid current which is within IEEE standards
- The passive damping method of LCL filter is a low cost solution and is used where efficiency can be sacrificed slightly
- The shunt connected LCL filter with parasitic elements has better performance than the series connected filter and increases the power injected into the grid

5.3 FUTURE SCOPE

- The grid connected RES system with the proposed control strategy can be simulated at various operating conditions like- grid faults and abnormalities
- The control strategy can also be implemented using any Artificial Intelligence (AI) techniques

REFERENCES

[1] Ma Liang; Zheng, T.Q., "Synchronous PI control for three phase grid-connected photovoltaic inverter," In Proc 2010 Chinese Control and Decision Conference (CCDC), pp.2302,2307, May 2010.

[2] Perera, Brian K., et al. "Simulation model of a grid-connected single-phase photovoltaic system in PSCAD/EMTDC." *Power System Technology (POWERCON), 2012 IEEE International Conference on*. IEEE, 2012.

[3] Li, Bin; Zhang, Ming; Huang, Long; Hang, Lijun; Tolbert, Leon M., "A robust multi-resonant PR regulator for three-phase grid-connected VSI using direct pole placement design strategy," *Applied Power Electronics Conference and Exposition (APEC), 2013 Twenty-Eighth Annual IEEE* , vol., no., pp.960,966, 17-21 March 2013.

[4] Hong-Seok Song; Keil, R.; Mutschler, P.; van der Weem, J.; Kwanghee Nam, "Advanced control scheme for a single-phase PWM rectifier in traction applications," *Industry Applications Conference, 2003. 38th IAS Annual Meeting. Conference Record of the* , vol.3, no., pp.1558,1565 vol.3, 12-16 Oct. 2003.

[5] Jiri Lettl, Jan Bauer, and Libor Linhart. “Comparison of Different Filter Types for Grid Connected Inverter” Progress In Electromagnetics Research Symposium Proceedings, PIERS Proceedings, pp 1426-1429, Marrakesh, Morocco, March 2011.

[6] Bochuan Liu; Byeong-Mun Song, "Modeling and analysis of an LCL filter for grid-connected inverters in wind power generation systems," *Power and Energy Society General Meeting, 2011 IEEE* , vol., no., pp.1,6, 24-29 July 2011.

[7] Hoff, B.; Sulkowski, W., "Grid connected VSI with LCL filter — Models and comparison," *Energy Conversion Congress and Exposition (ECCE), 2012 IEEE* , vol., no., pp.4635,4642, 15-20 Sept. 2012.

[8] Wenqiang Zhao; Guozhu Chen, "Comparison of active and passive damping methods for application in high power active power filter with LCL-filter," *Sustainable Power Generation and Supply, 2009. SUPERGEN '09. International Conference on* , vol., no., pp.1,6, 6-7 April 2009.

[9] Blaabjerg, F.; Teodorescu, R.; Liserre, M.; Timbus, A.V., "Overview of Control and Grid Synchronization for Distributed Power Generation Systems," *Industrial Electronics, IEEE Transactions on* , vol.53, no.5, pp.1398,1409, Oct. 2006.

[10] Anees, A.S., "Grid integration of renewable energy sources: Challenges, issues and possible solutions," *Power Electronics (IICPE), 2012 IEEE 5th India International Conference on* , vol., no., pp.1,6, 6-8 Dec. 2012.

[11] Sang-Hyub Han; Jong-Hyoung Park; Heung-Geun Kim; Honnyong Cha; Tae-Won Chun; Eui-Cheol Nho, "Resonance damping of LCL filter based grid-connected inverter," *Power Electronics and Motion Control Conference (IPEMC), 2012 7th International* , vol.2, no., pp.796,800, 2-5 June 2012.

[12] Buticchi, G.; Franceschini, G.; Lorenzani, E.; Tassoni, C.; Bellini, A., "A novel current sensing DC offset compensation strategy in transformerless grid connected power converters," *Energy Conversion Congress and Exposition, 2009. ECCE 2009. IEEE* , vol., no., pp.3889,3894, 20-24 Sept. 2009.

[13] Channegowda, P.; John, V., "Filter Optimization for Grid Interactive Voltage Source Inverters," *Industrial Electronics, IEEE Transactions on* , vol.57, no.12, pp.4106,4114, Dec. 2010.

[14] Hanif, M., "Active damping techniques for suppressing the LCL filter resonance in distributed generators," *Power Engineering Conference (UPEC), 2013 48th International Universities'* , vol., no., pp.1,5, 2-5 Sept. 2013.

[15] Teodorescu, R.; Blaabjerg, F.; Liserre, M.; Loh, P.C., "Proportional-resonant controllers and filters for grid-connected voltage-source converters," *Electric Power Applications, IEE Proceedings* , vol.153, no.5, pp.750,762, September 2006.

[16] Huafeng Xiao; Xiaohui Qu; Shaojun Xie; Jinming Xu, "Synthesis of active damping for grid-connected inverters with an LCL filter," *Energy Conversion Congress and Exposition (ECCE), 2012 IEEE* , vol., no., pp.550,556, 15-20 Sept. 2012.

[17] Hanif, M.; Khadkikar, V.; Weidong Xiao; Kirtley, J.L., "Two Degrees of Freedom Active Damping Technique for Filter-Based Grid Connected PV Systems," *Industrial Electronics, IEEE Transactions on* , vol.61, no.6, pp.2795,2803, June 2014.

[18] Maknouninejad, A.; Simoes, M.G.; Zolot, M., "Single phase and three phase P+Resonant based grid connected inverters with reactive power and harmonic compensation capabilities," *Electric Machines and Drives Conference, 2009. IEMDC '09. IEEE International* , vol., no., pp.385,391, 3-6 May 2009.

[19] Hong-Ju Jung; Keun-Soo Ha; Byeong-Mun Song; Jih-Sheng Lai; Dong-Seok Hyun; Rae-young Kim, "Low frequency current reduction using a quasi-notch filter operated in two-stage DC-DC-AC grid-connected systems," *Energy Conversion Congress and Exposition (ECCE), 2011 IEEE* , vol., no., pp.2746,2750, 17-22 Sept. 2011.

[20] Xuehua Wang; Xinbo Ruan; Chenlei Bao; Donghua Pan; Lin Xu, "Design of the PI regulator and feedback coefficient of capacitor current for grid-connected inverter with an LCL filter in discrete-time domain," *Energy Conversion Congress and Exposition (ECCE), 2012 IEEE* , vol., no., pp.1657,1662, 15-20 Sept. 2012.

[21] Liserre, M.; Blaabjerg, F.; Hansen, S., "Design and control of an LCL-filter-based three-phase active rectifier," *Industry Applications, IEEE Transactions on* , vol.41, no.5, pp.1281,1291, Sept.-Oct. 2005.

[22] M. Hojabri, A. Z. Ahmad, A. Toudeshki and M. Soheilirad, "An Overview on Current Control Techniques for Grid Connected Renewable Energy Systems," 2nd International Conference on Power and Energy Systems (ICPES), November 2012, pp. 119-126.

[23] June-Seok Lee; Duk-Hong Kang; Hea-Gwang Jeong; Kyo-Beum Lee, "Active damping for large-scale wind power systems with an LCL-filter using an improved DFT," *IECON 2011 - 37th Annual Conference on IEEE Industrial Electronics Society* , vol., no., pp.1179,1184, 7-10 Nov. 2011.

[24] C. Bajracharya, M. Molinas, J. A. Suul, T. Undeland, "Understanding of tuning techniques of converter controllers for VSC-HVDC," in Proceedings of NORPIE 2008, Helsinki, Finland, 09-11 June 2008.

[25] F. Blaabjerg, Z. Chen, and S. Kjaer, "Power electronics as efficient interface in dispersed power generation systems," *IEEE Trans. Power Electron* vol. 19, no. 5, pp. 1184–1194, Sep. 2004.

[26] O.Siddique, "*The Green Grid: Energy Savings and Carbon Emission Reductions Enabled by a Smart Grid,"* EPRI Palo Alto, CA: 2008.

[27] Dash, A.R, Babu, B.C, Mohanty, K.B., Dubey, R., "Analysis of PI and PR Controllers for Distributed Power Generation System under Unbalanced Grid Faults", In Proc. IEEE International Conference on Power and Energy Ssytems (ICPS 2011), pp. 1-6, Dec. 2011.

[28] Elbuluk, M.; Idris, N.R.N., "The role power electronics in future energy systems and green industrialization," *Power and Energy Conference, 2008. PECon 2008. IEEE 2nd International* , vol., no., pp.1,6, 1-3 Dec. 2008.

[29] Bhende, C.N.; Mishra, S.; Malla, S.G., "Permanent Magnet Synchronous Generator-Based Standalone Wind Energy Supply System," *Sustainable Energy, IEEE Transactions on* , vol.2, no.4, pp.361,373, Oct. 2011.

[30] Hayashiya, H.; Akagi, M.; Konishi, T.; Okui, A., "Survey of power electronics and electric machine application for on-site railway power system in Japan to realize eco-friendly transportation," *Power Electronics and Motion Control Conference (EPE/PEMC), 2010 14th International* , vol., no., pp.S7-17,S7-24, 6-8 Sept. 2010.

PUBLICATIONS

1. **M. Lakshmi Sowjanya**, B. Chitti Babu, "Comparative Analysis of LCL Filter with Active and Passive Damping Methods for Grid-interactive Inverter System" Proc. Of IEEE Student's Technology Symposium 2014 (TECHSYM 2014), IIT Kharagpur, March 2014. pp. 350-355.